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Prioritizing sustainable electricity production technologies: MCDM approach

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ABSTRACT

Economic, technological, social, and political developments stressed the need for shifts in energy-mix. Therefore it is important to provide a rationale for sustainable decision making in energy policy. The aim of this paper is to develop the multi-criteria decision support framework for choosing the most sustainable electricity production technologies. Given selection of sustainable energy sources involves many conflicting criteria, multi-criteria decision methods MULTIMOORA and TOPSIS were employed for the analysis. The indicator system covering different approaches of sustainability was established. The analysis proved that the future energy policy should be oriented towards the sustainable energy technologies, namely water and solar thermal ones. It is the proposed multi-criteria assessment framework that can constitute a basis for further sub-regional optimization of sustainable energy policy.

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1. Introduction

Shifts in energy-mix have always been omnipresent throughout the history. As Solomon and Krishna [1] argued, it is natural to shift between energy sources as local resource scarcity, convenience, pollution, technical innovation, cost, energy quality, storage, and other factors come into play; people are not required to keep using a particular source if better options become available.

The recent economic, technological, social, and political developments stressed the need for increase in both sustainability and diversification of energy sources. To be specific, it is the global climate change and rising petroleum prices that shape energy policy. The Kyoto Protocol of 1997 defined the main aims of the contemporary economic, industrial, and energetic development in terms of greenhouse gas emission mitigation. The strategy *Europe 2020* [2] can be mentioned as one of the most recent manifestations of suchlike incentives in the European Union. Furthermore, Omer [3] argued that energy is the main intermediate good for socio-economic development in any country. Accordingly, energy efficiency constitutes the foremost goal contemporary energy policy.

Over the last decade, the impact of "sustainability" on the development of national and international policy has increased. Efforts towards a sustainable energy system are progressively becoming an issue of paramount importance for decision makers. Efficient production, distribution, and use of energy resources coupled with provision of equitable and affordable access to energy simultaneously ensuring security of energy supply and environmental sustainability constitute the main energy policy objectives for a

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sustainable energy system. Implementation of new energy technologies is a key mean towards a sustainable energy system. Technological advances are of critical importance for the improvement of living conditions, the production and the transportation of the energy and the efficiency of its use thus it is expected to produce major public benefits. New energy technologies can be considered to be an important bridge between the *Europe 2020* objectives and the EU Sustainable development strategy adopted at the Goteborg European Council.

Indeed, the very selection of sustainable energy sources involves multiple conflicting objectives. It is therefore important to develop multi-criteria decision support frameworks for sustainable energy policy. Multi-criteria decision making (MCDM) methods are suitable to tackle energy source selection problem [4,5].

Roy [6] presented the following pattern of MCDM problems: (1) α *choosing* problem – choosing the best alternative; (2) β *sorting* problem – classifying alternatives into relatively homogenous groups; (3) γ *ranking* problem – ranking alternatives from best to worst; (4) δ *describing* problem – describing alternatives in terms of their peculiarities and features. Due to Løken [7], Belton and Stewart [8] defined the three broad categories of MCDM methods: (1) value measurement models; (2) goal, aspiration, and reference level models; (3) outranking models (the French school). A number of the recent studies, therefore, dealt with application of MCDM in energy policy [9–16]. In this study we will apply two MCDM methods, namely MULTIMOORA and TOPSIS for a more robust assessment. The MULTIMOORA method was developed by Brauers and Zavadskas [17–19], whereas TOPSIS was offered by Hwang and Yoon [20].

The aim of this paper is to develop the multi-criteria decision support framework for choosing the most sustainable electricity production technologies. The paper is organized as follows. Section 2 describes the two MCDM methods applied for the complex assessment of electricity production technologies. The following Section 3 discusses the alternatives of electricity production as well as criteria for comparison of these technologies. Finally, Section 4 brings the results of the comparison of electricity production technologies.

2. Preliminaries for MCDM

This section describes the two MCDM methods which will be employed for prioritization of the electricity production technologies. The first method is MULTIMOORA. Indeed, it originated from Multi-Objective Optimization by Ratio Analysis (MOORA) method introduced by Brauers and Zavadskas [17] on the basis of previous research. The same authors [18,19] extended the method and in this way it became more robust as MULTIMOORA (MOORA plus the full multiplicative form). In order to check the consistency of the obtained ratings, the second MCDM method, namely TOPSIS [20,21], was employed for the analysis.

2.1. The MULTIMOORA method

The MULTIMOORA method begins with a response matrix X where its elements x_{ij} denote ith alternative of jth objective ($i = 1, 2, ..., m$ and $j = 1, 2, ..., n$). The method consists of three parts, viz. the Ratio System, the Reference Point approach, and the Full Multiplicative Form.

The Ratio System of MOORA. Ratio system employs the vector data normalization by comparing alternative of an objective to all values of the objective:

$$x_{ij}^* = w_j \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \tag{1}$$

where x_{ij}^* denotes ith alternative of jth objective and w_j is weight of the jth criterion, $\sum_j w_j = 1$. In the absence of negative values, these numbers belong to the interval [0; 1]. These indicators are added (if desirable value of indicator is maximum) or subtracted (if desirable value is minimum). Thus, the summarizing index of each alternative is derived in this way:

$$y_i^* = \sum_{j=1}^{g} x_{ij}^* - \sum_{j=g+1}^{n} x_{ij}^*, \tag{2}$$

where $g = 1, 2, ..., n$ denotes number of objectives to be maximized. Then every ratio is given the rank: the higher the index, the higher the rank.

The Reference Point of MOORA. Reference point approach is based on the Ratio System. The Maximal Objective Reference Point (vector) is found according to ratios found in Eq. (1). The jth coordinate of the reference point can be described as $r_j = \max_i x_{ij}^*$ in case of maximization. Every coordinate of this vector represents maximum or minimum of certain objective (indicator). Then every element of the normalized response matrix is recalculated and final rank is given according to deviation from the reference point and the Min-Max Metric of Tchebycheff:

$$\min_i (\max_j |r_j - x_{ij}^*|). \tag{3}$$

The Full Multiplicative Form and MULTIMOORA. Brauers and Zavadskas [18] proposed MOORA to be updated by the Full Multiplicative Form method embodying maximization as well as minimization of purely multiplicative utility function. Overall utility of the ith alternative can be expressed as dimensionless number:

$$U_i' = \frac{A_i}{B_i}, \tag{4}$$

where $A_i = \prod_{j=1}^{g} (x_{ij})^{w_j}$ denotes the product of objectives of the ith alternative to be maximized with $g = 1, \ldots, n$ being the number of objectives to be maximized and where $B_i = \prod_{j=g+1}^{n} (x_{ij})^{w_j}$ denotes the product of objectives of the ith alternative to be minimized with $n - g$ being the number of objectives (indicators) to be minimized. Thus MULTIMOORA summarizes MOORA (i.e. Ratio System and Reference point) and the Full Multiplicative Form. Brauers and Zavadskas [19] proposed the dominance theory to summarize the three ranks provided by different parts of MULTIMOORA.

Absolute Dominance means that an alternative, solution or project is dominating in ranking all other alternatives, solutions or projects which are all being dominated. This absolute dominance shows as rankings for MULTIMOORA: (1–1–1). *General Dominance in two of the three methods* is of the form with a < b < c < d:

(d–a–a) is generally dominating (c–b–b);
(a–d–a) is generally dominating (b–c–b);
(a–a–d) is generally dominating (b–b–c);

and further transitiveness plays fully.

Transitiveness. If a dominates b and b dominates c than also a will dominate c. *Overall Dominance of one alternative on the next one.* For instance (a–a–a) is overall dominating (b–b–b) which is overall being dominated, with (b–b–b) following immediately (a–a–a) in rank (transitiveness is not playing). *Absolute Equability* has the form: for instance (e–e–e) for 2 alternatives. *Partial Equability* of 2 on 3 exists, e.g. (5–e–7) and (6–e–3). Despite all distinctions in classification some contradictions remain

possible in a kind of *Circular Reasoning*. We can cite the case of:

Object A (11–20–14) ≻ Object B. (14–16–15);
Object B (14–16–15) ≻ Object C (15–19–12); but
Object C (15–19–12) ≻ Object A (11–20–14).

Here, the operator ≻ represents a *General Dominance*. In such a case the same ranking is given to the three objects.

2.2. The TOPSIS method

The algorithm of TOPSIS method is presented according to Hwang and Yoon [20] and Antuchevičienė et al. [21]. The TOPSIS method will use the same normalized weighted values from Eq. (1), thus $x^*_{ij} = v_{ij}$.

Firstly, positive-ideal and negative-ideal solutions, denoted respectively as A^* and A^-, are identified in the following way:

$$A^* = \{(\max_i v_{ij} | j \in I), (\min_i v_{ij} | j \in I'), i = 1, 2, \ldots, m\} = \{v_1^*, v_2^*, \ldots, v_m^*\}, \quad (5)$$

$$A^- = \{(\min_i v_{ij} | j \in I), (\max_i v_{ij} | j \in I'), i = 1, 2, \ldots, m\} = \{v_1^-, v_2^-, \ldots, v_m^-\}, \quad (6)$$

where $I = \{j = 1, 2, \ldots, n\}$ and $I' = \{j = 1, 2, \ldots, n\}$ are sets of benefit and cost criteria, respectively. The n-dimensional Euclidean distance then measures the distances of each alternative from the positive-ideal solution and the negative-ideal solution:

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}, \quad \text{for} \quad i = 1, 2, \ldots, m \quad (7)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, \quad \text{for} \quad i = 1, 2, \ldots, m \quad (8)$$

with v_j^* and v_j^- being obtained from Eqs. (5) and (6), respectively. Finally, the relative similarity to the positive-ideal solution is calculated (proximity to positive and remoteness to negative values):

$$C_i = \frac{S_j^-}{S_j^* + S_j^-}, \quad (9)$$

where $C_i \in [0; 1]$ with $i = 1, 2, \ldots, m$. The best alternative can therefore be found according to the preference order of C_i.

3. Indicator framework for sustainability assessment of energy technologies

This section focuses on the system of indicators identifying long-term sustainability of the energy technologies. In addition, the energy production alternatives are provided.

A literature survey aiming at a review of published criteria and indicators applied for energy technologies assessment was conducted [22–31]. It enabled to identify the most important criteria for comparison of energy production technologies. Some authors analyse sustainability assessment indicators just for renewables [22,23,25,26,31] or nuclear [29]. Other authors were developing indicators for sustainability assessment to support decision making in electricity sector [24,27,28,30]. Table 1 presents the full set of indicators covering economic, environmental, and social aspects for long-term sustainability assessment of energy technologies based on the acceptance of indicators in various studies. The most popular indicators were selected to address the EU energy policy priorities. Therefore the proposed indicator framework addresses the EU energy and environmental policy priorities and the three dimensions of sustainable development.

The following sub-sections describe each indicator in-depth.

3.1. Economic indicators

The Economic dimension in sustainability assessment of energy technologies is very important as energy supply cost is the main driver for energy technologies penetration in the markets. There are 6 indicators selected to address economic dimension of sustainability assessment in electricity and heat sector: private costs, fuel price increase sensitivity, average availability factor, costs of grid connection, peak load response, security of supply. The most important indicators are: private costs, availability factor and costs of grid connection.

The private costs in EURcnt/kWh are based on the Average Levelized Generating Costs (ALLGC) methodology [32–38]. The methodology calculates the generation costs (in EuroCents/kWh) on the basis of net power supplied to the station busbar, where electricity is fed to the grid. This cost estimation methodology discounts the time series of expenditures to their present values in 2005, which is the specified base year, by applying a discount rate. According to the methodology used in the IEA study in 2005, the levelized lifetime cost per GWh of electricity generated is the ratio of total lifetime expenses versus total expected outputs, expressed in terms of present value equivalent. The total lifetime expenses include the value of the capital, fuel expenses and operation and maintenance expenses, inclusive the rate of return equal to discount rate. The formula to calculate average lifetime levelized generating costs is:

$$\text{ALLGC} = \frac{\sum_{t=0}^{T} [I_t + M_t + F_t]/(1+r)^t}{\sum_{t=0}^{T} [E_t]/(1+r)^t} \quad (10)$$

where I_t is the investment expenditures in year t; M_t is the operation and maintenance expenditure in year t; F_t is the fuel expenditures in year t; E_t is the electricity generation in year t and r is the discount rate.

The capital (investment) expenditures in each year include construction, refurbishment and decommissioning expenses. As suggested by OECD the methodology used defines the specific overnight construction cost in €/kW and the expense schedule from the construction period. The overnight construction cost is defined as the total of all costs incurred for building the plant immediately.

The operating and maintenance costs (O&M) contribute by a small but no negligible fraction to the total cost. Fixed O&M costs include costs of the operational staff, insurances, taxes etc. Variable O&M costs include cost for maintenance, contracted personnel, consumed material and cost for disposal of normal operational waste (excluding radioactive waste).

The fuel price assumptions for fossil and nuclear plants are based on results from EUSUSTEL project [34]. The technical life time for various types of power plants are also obtained from EUSUSTEL project. Since lignite and biomass are local energy carriers, which are not included in an international price mechanism, then the fuel prices of these two types of energy carriers are assumed to be constant. The price projections for the other fuels are determined by taking into account the international market mechanism. Of particular noteworthiness for nuclear power is that the total fuel cycle costs are considered (natural uranium, conversion, enrichment, intermediate and final disposal).

The ALLGC for combined heat and power plants (CHP) does not take into account the fact that the plant is used also to produce heat, in addition to electricity. The value of heat recovery can be

Table 1
Indicator set for long-term sustainability assessment of electricity generation technologies.

Acronym	Indicator	Units of measurement	Information sources
Economic dimension			
PR COST	Private costs (investments and operation costs)	EURcnt/kWh	[32,33]
AVAILAB	Average availability (load) factor	%	[34]
SECURE	Security of supply	Point	[35–37]
GRID COST	Costs of grid connection	Point	[32,33]
PEAK LOAD	Peak load response	Point	[35–38]
Environmental dimension			
CO_2eq.	GHG emissions	kg/kWh	[32,33]
ENV	Environmental external costs	EURcnt/kWh	[32,33]
RADIO	Radionuclide external costs	EURcnt/kWh	[32,33]
HEALTH	Human health impact	EURcnt/kWh	[32,33]
Social dimension			
EMPL	Technology-specific job opportunities	Person-year/kWh	[38]
FOOD	Food safety risk	Point	[32,33]
ACC PAST	Fatal accidents from the past experience	Fatalities/kWh	[38]
ACC FUT	Severe accidents perceived in future	Point	[32,33]

measured by the cost avoided in using recovered thermal energy for a specific purpose, as opposed to using another source of energy. The value of recovered thermal energy is equivalent to the cost of fuel energy that would have otherwise been consumed, which is referred to as an energy credit or fuel credit. A gas boiler, with an efficiency of 90 percent, gives the alternative heat generation technology in this report. Then in the computation of full cost the fuel credit is subtracted from the ALLGC.

An adjustment of the ALLGC should be made also for wind and solar technologies. Due to the fluctuation caused by producing energy with wind and solar plants, which are intermittent energy sources, a back-up technology is necessary for compensating this. The back-up cost of uncertain generating power of solar and wind plants are calculated with the equation estimated in [38]. In this equation, the provision of the back-up power is reduced by a capacity factor (P) for the renewable technologies. In the calculation of full costs the ALLGC is summed to the back up cost of a gas-fired CCGT plant for maximum back-up costs. The methodology described determines for each technology a private cost of electricity production levelized for all Europe. To reach the objective of comparability, country specific cost components are not considered. In particular the estimation is not influenced by the capital market's differences across Europe since overnight investments costs are considered. In addition all costs are considered net of taxes, which change from country to country. To assess full costs of electricity production a discount rate of 5 percent is considered. The basis year for the analysis is 2005. This indicator was applied in all studies on energy technology assessment reviewed in report. European values for 2030 will be applied for electricity generation technologies assessment in this report.

Costs for grid connection (points 1–5) indicator is additional qualitative indicator to assess the risk that a certain technology will include high cost for grid connection as private costs of electricity generation do not include costs related to grid connection. The higher the score the higher risks of high cost for grid connection, for example wind off-shore electricity generation has the highest grid connection costs. This indicator was used in just in CASES project to assess electricity generation technologies [32,33].

Peak–load response (points 0–5) is qualitative indicator which reflects the technology-specific ability to respond swiftly to large temporal variations in demand. This capability is particularly attractive in view of market liberalization. Base-load technologies, and those renewables which strongly depend on climatic conditions, are not suitable in this context and has very low score. This indicator was applied in NEEDS [25,36], PSI [38] studies just other scales for scoring were applied. As in PSI and NEEDS flexibility to dispatch was evaluated on an ordinal scales ranging from 0 to 100 and from 1 to 10 scores, respectively. For the dispatchable technologies, such as hard coal, lignite, natural gas, oil based and hydro technologies a score between 1 and 5 is allocated and for non-dispatchable technologies such as solar and wind – 0 score is allocated (Table 2).

Table 2
Values for peak–load response.

Fuels	Value
Nuclear	0.5
Fuel cells	0.5
Hard coal	2.5
Lignite	1
Oil	5
Natural gas	5
Hydro	1.5
Biomass	5
PV	0
Wind	0

Average availability factor (%) is based on typical load factors. This information for specific power plants is presented in EUSUSTEL project and available in NEEDS and PSI [34–38].

Security of energy supply is a qualitative indicator (points 1–5) and it is very important from the point of view of EU energy policy priorities. The security of supply in electricity sector can be expressed by Long-term independence from foreign energy source. This indicator was applied for evaluation of autonomy of electricity generation in NEEDS project [35,36].

Utility companies and the societies they serve may be vulnerable to interruptions in service if imported fuels are unavailable due to economic or political problems related to energy resource availability. It combines consideration of energy autonomy and sustainability, based on whether the energy resource for a specific technology is imported, domestic and finite, or domestic and renewable, with some weight given to the relative size of different finite resources. The quantification of this indicator is proposed to follow an ordinal scale, as given in Table 3.

The scale given runs from zero for energy carriers that must be imported to 5 for renewable resources that are domestically available. Intermediate values for domestic fossil or nuclear resources are based on judgement of the relative time scales for the availability of different fuel types, and some consideration of domestic interaction with global markets. For this indicator, the fuel refers to the primary energy carrier, e.g. synthetic gas made from biomass would be scored a 5, while synthetic gas made from coal would be scored a 3, and natural gas would be scored a 2. This distinction also applies to synthetic oil from various sources v. oil refined from domestic crude reserves.

Table 3
Values for the indicator "very long-term independence from foreign energy sources" (NEEDS, 2006).

Group name	Value	Description
Imported energy carrier	0	Technologies that rely on fuels or energy sources that must be imported
Domestic oil	1	For oil-fired technologies in countries where domestic oil resources are available
Domestic gas	2	For gas-fired technologies in countries where domestic gas resources are available
Domestic coal	3	For coal-fired technologies in countries where domestic coal resources are available
Domestic uranium	4	For nuclear technologies in countries where domestic uranium resources are available
Fuel cells	3	Fuel cells are based on natural gas or biogas therefore average score can be applied
Domestic renewable resource	5	For technologies which rely on renewable energy fluxes present in a given country (hydro, solar, wind, wave, geothermal)

Several possible indicators were originally proposed in various studies to measure the contribution of each generating technology to the autonomy of electricity supply. The indicator for short-term autonomy proposed in NEEDS project was the lifetime of stored reserves (i.e. short-term stockpiles/current resource use). Estimating future stockpiles and use for the year 2050 however was so uncertain and scenario dependent that this indicator was abandoned. An indicator for long-term autonomy based on domestic energy resources was also proposed, based on long-term reserve life (i.e. currently known and recoverable domestic reserves/current domestic use) in NEEDS project [35,36]. There was still considerable uncertainty as to how well this current measure of resource lifetime would apply in the year 2050, but it was deemed acceptable due to the long-term resource life. Modifications based on the substitutability of fuels were also considered and rejected. However the main problem with using the concept of resource life as an indicator remained that it essentially produces a binary measure. That is, fossil & uranium reserves are finite, no matter how large, and renewables have a resource life that is infinite for all practical purposes. This binary separation of finite v. infinite destroys the possibility of making any discrimination between the different resource lifetimes for the different fossil and nuclear technologies, which are still of significant importance.

It was proposed to resolve this difficulty by imposing an arbitrary, large cap on the resource life of the renewable resources, but it was unclear what the rationale for this should be. Likewise, it would have been possible to use the logarithm of the resource life, which would have compressed the difference between finite and renewable resources, but not really have solved the problem. In the end, it seemed more reasonable to recognize the inherent element of judgement, and the ordinal scale given above was proposed. This element of judgement also allows some recognition of the fact that finite resources with similar resource lifetimes may still have different risks associated with geographic distribution, market forces and international politics.

The evaluation of whether domestic energy resources are available is based on expert judgment, i.e. whether it is now thought that there is sufficient domestic fuel resource to build a generation unit in 2050 and operate it economically for its life. If fossil fuels or uranium are not now domestically present, then the situation is clear. If coal, lignite or uranium is present, then the reserves are likely to last for the commercial life of the plant (40+ years). The situation for oil and particularly gas reserves is more complicated.

3.2. Environmental indicators

The main environmental dimension indicators for energy technologies assessment are: GHG emissions, environmental external costs, radionuclides external costs, severe accidents perceived in future and fatal accidents from the past experience. Additional environmental indicators are land use and solid waste.

Life cycle emissions of GHG emissions in kg (CO_2-eq.)/kWh are selected to assess electricity generation technologies according EU environmental policy priority – climate change mitigation. GHG emissions in kg CO_2eq./kWh were selected instead of external costs of GHG emissions because of the large uncertainties related to evaluation of external costs of GHG emissions. Climate change is the dominating environmental concern of the international environmental political discussion of today. Global warming is not only an issue for the environment, but rather for human society as a whole, since rising global temperatures might have serious consequences not only on the environment, but on our economy and social life as well. Among the potential consequences are more frequent extreme weather events like heat waves, storms, flooding and droughts, stress due to higher temperatures for plants and humans, rising sea level, and altering occurrence of pathogenic organisms. The indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity. This indicator was used in almost all studies on energy technologies assessment survived [32–38].

The environmental external costs in EURcnt/kWh is the estimates for damage to ecosystems due to emissions to air, soil and water of particles, gases, the formation of ozone and the emissions of metals. These costs were obtained during ExternE, NEEDS and CASES projects and were used in these projects for electricity generation technologies assessment. Environmental external costs are calculated with respect to the impact of pollutants on crops, damage to materials, and loss of biodiversity caused by acidification and eutrophication. For all these categories of impact the life cycle emissions of air pollutants are considered: Ammonia (NH_3), Non-methane volatile organic compounds unspecified (NMVOC), Nitrogen oxides (NOx), Particulates (PPMco – between 2.5 and 10 μm, and PPM25 – less than 2.5 μm), Sulphur dioxide (SO_2). In addition the cost of sulphur dioxide and nitrogen oxides emissions in the atmosphere is calculated with respect to the damage to materials. The European values for 2030 will be applied for assessment of electricity generation technologies in this report [32–36].

The external health costs in EURcnt/kWh provide the estimates for damages to health due to emissions to air, soil and water of particles, gases, the formation of ozone, and emissions of metals. Marginal external costs for classical air pollutants were calculated for CASES project by IER with the updated EcoSenseWebV1.2 tool. To estimate external costs by transforming impacts that are expressed in different units into a common monetary unit, the ExternE methodology is used. The costs of emission are calculated with respect to the impact of pollutants on human health for all these categories of impact the following air pollutants are considered: Ammonia (NH_3), Non-methane volatile organic compounds unspecified (NMVOC), Nitrogen oxides (NOx), Particulates (PPMco – between 2.5 and 10 μm, and PPM25 less then 2.5 μm), Sulphur dioxide (SO_2). The European averaged values for 2030 will be applied for electricity technologies assessment in this project [32,33,35,36].

Radionuclides external costs in EURcnt/kWh are external costs estimates for damages to health due to emissions of life cycle radionuclides including indirect use of nuclear electricity in the production of other technologies. The release of these radionuclides

and the corresponding radioactivity into the environment causes impacts to human health. The impacts considered are fatal cancers, non-fatal cancers and hereditary defects. The cost in Euro/kBq is obtained by multiplying the collective dose estimation unit (manSv) per kBq, which is specific for each pollutants, times the cases of fatal cancer, non fatal cancer and hereditary defects per manSv and the corresponding Willingness To Pay (WTP) values in Euro per endpoint. The factors relating collective dose to impact, so called risk factors, are determined by a linear dose-effect relationship. The values used in calculation are: 0.05 cases per manSv for fatal cancers, 0.12 cases per manSv for non-fatal cancers and 0.01 cases per manSv for hereditary defects. To calculate the cost in Euro/kBq for radionuclide unit of emission the respective number of cases of endpoint per kBq is multiplied by the following values for WTP per endpoint: 1,120,000 Euro for fatal cancers, 481,000 for non-fatal cancers and 1,500,000 for hereditary defects 10. These WTP values are derived from estimates for different types of cancer, e.g. leukaemia, lung cancer, etc. Types of cancer differ in latency and estimated YOLL and YLD (year lost due to disability). For fatal cancers, 15.95 YOLL + 0.26 YLD are assumed. The monetary value for fatal cancer includes also an additional estimation of WTP to avoid the illness based on the costs of illness (COI) (ca. 481,050 E) The YOLL are multiplied with 40,000 Euro/year of life lost. Heredity effects have been valued at the same value as a statistical life, since there are no WTP estimates of such impacts available, and given the relevance usually attributed to such effects. Generic marginal external radionuclides cost were estimated for the following radionuclides: Aerosols, radioactive, unspecified into air; Carbon-14 into air and water; Hydrogen-3, Tritium into air and water; Iodine-129 into air; Iodine-131 into air; Krypton-85 into air; Noble gases, radioactive; unspecified into air; Radon-222 into air; Thorium-230 into air and water; Uranium-234 into air and water. The radionuclides external costs estimates are based on ExternE, NEEDS and Cases project results. The European values for 2030 will be applied for evaluation of electricity generation technologies in this report [32,33,35,36].

3.3. Social indicators

The main social indicators selected for electricity technologies assessment in this report are technology-specific job opportunities, human health impact, food safety risk and work related fatalities per accident. The most important indicators applied in almost all studies for technologies assessment are: external health costs and technology specific job opportunities.

Technology specific job opportunities in person-year/kWh indicator are based on the average amount of labour used to produce a unit of electricity. It does not give the total number of persons employed (some jobs might be part-time), or the quality of the jobs as measured either by salary or the amount of training or education required. The quality of work issue is instead addressed by one of the social indicators (the "Work Quality" indicator is based on knowledge and training of average worker in each technology chain), using an ordinal scale indicator. The aim of the technology chain labour assessment was to estimate the life-cycle labour content of 8 technology chains for electricity generation, including lignite pulverized coal, bituminous pulverized coal (hard coal), oil, natural gas, hydro, wind and solar PV generation. In order to do this, each chain was divided into four components: (1) Fuel Extraction & Processing; (2) Fuel Transportation; (3) Generation Plant Construction; and (4) Generation Plant Operation.

It is difficult to find hard data for establishing accurate, averaged labour statistics for these technologies across the entire EU electricity sector. National electricity sector associations do not collect employment numbers by fuel-type or type of plant. The only official number from these organizations is the total employment level of 131,000 for the German electricity sector. Normalizing by the total net generation of about 520 TWh in 2002 gives an average employment of about 250 man-year/TWh. If the more detailed US employment data ratios are applied, this would result in about 110 man-year/TWh for generation, transmission and distribution (T&D), and about 240 man-year/TWh for general and administrative jobs. These data can serve as an order of magnitude check against individual generation technologies, although they do include non-generation components, and do not include T&D employment.

Overall, the estimation of labour can be followed by 3 possible methods. When national data (e.g. mining jobs) were available, they were used to obtain a national sector average. If industry sources were available for specific plant types (e.g. generation labour for combined-cycle plants), these were used next. Finally, order-of-magnitude estimates were made (e.g. for average hydro construction labour) when other sources failed. Total uncertainty depends upon both the relative sizes and uncertainties of the labour estimates for the individual technology chain components. Two other factors also affect the uncertainty of labour estimates. First is the question of where the dividing boundary should be. For example, in the case of coal and nuclear generation, direct plant construction labour was estimated for on-site construction, and excluded the specific labour content of components. However, for the wind and solar technology chains, more indirect aggregate industry construction data were used, based on data availability, and the fact that more of the labour is devoted to component fabrication. Secondly, labour results have been normalized in terms of generation; i.e. they were given in man-years per TWh. This means that variable labour (e.g. fuel) depends upon plant efficiency, and fixed labour (e.g. construction) depends upon plant generation. Some electricity generation (e.g. by wind and solar) is fixed by natural availability, but most generation is based on cost-based dispatch. In this case, the generation was based on the German average generation for the technology in question. Finally, labour components for different technologies were compared and adjusted, based on our own estimates of the relative labour intensity required. It should be noted that all non-recurring labour (primarily construction labour) was amortized over the assumed life of the generation technology before adding the variable labour content for fuel, etc. This means that labour rates for the different labour components can be multiplied by the labour content to produce a total labour cost per kWh, if so desired. Finally, the relative sizes of the individual labour components and totals were compared for general consistency, and adjusted as deemed appropriate [32,33,38].

Food safety risk is qualitative indicator (points 1–5) used for qualitative assessment of the risk that using biomass fuels will put stress on food supply safety and food prices. This indicator was applied for technologies assessment in CASES project is very relevant today as the increased use of biomass especially for biofuels production in transport cause big problems related with increase of food prices.

Fatal accidents from past experience in fatalities/kWye indicator represents the risk of fatal accident using the frequency of occurrence o a severe accident in the past and the number of fatalities involved in previous accidents. In principle, the approach used for the evaluation of severe accidents is consistent with the impact pathway method. Due to their special nature, however, accidents are treated separately. The evaluation builds on other work carried out at PSI and covers fossil energy sources (coal, oil and gas), nuclear power and hydropower. PSI's database ENSAD (Energy-related Severe Accidents Database) was developed. This indicator was also widely applied in energy technologies assessment studies, i.e. NEEDS, CASES, PSI [32,33,35–38].

Table 4
Electricity and heat generation technologies selected for multi-criteria sustainability assessment.

Technologies and types of power plants			Acronyms
Electricity production			
Nuclear		EPR	NUC
Fossil fired power plants	Oil	Heavy oil condensing PP	OIL CL
		Light oil gas turbine	OIL GT
	Coal	Condensing PP	COA CL
		IGCC	COA IGCC
		IGCC PP with CO_2 sequestration	COA IGCC CCS
	Lignite	Condensing pp	LIG CL
		IGCC	LIG IGCC
		IGCC pp with CO_2 sequestration	LIG IGCC CCS
	Gas	Combined cycle	GAS STAG
		Combined cycle PP with CO_2 sequestration	GAS STAG CCS
		Gas turbine	GAS GT
Hydropower	Run of river	<10 MW	HYD S
		<100 MW	HYD M
		>100 MW	HYD L
	Dam		HYD DAM
	Pump storage		HYD PMP
Wind	On shore		WIND ON
	Off shore		WIND OFF
Solar PV	Roof		PV ROOF
	Open space		PV OPEN
Solar thermal			SOL TH
Electricity and heating production (CHP)			
CHP with an extraction condensing turbine	Gas	CC	CHP GAS
		CC PP with CO_2 sequestration	CHP GAS CCS
	Coal	PP	CHP COAL
		IGCC PP with CO_2 sequestration	CHP COAL CCS
CHP back pressure	Gas		CHP GAS STAG
	Coal		CHP COAL BP
Biomass CHP with an extraction condensing turbine	Straw		CHP STRAW
	Wood chips		CHP WOOD
Fuel cells	Natural gas	MCFC	MCFC
		SOFC	SOFC
	Bio gas	MCFC	MCFC BG

Severe accidents perceived in the future are qualitative indicator (points 1–5) and represents qualitative assessment of risk of a severe accidents in the future. The higher the score the more people perceive that accident will happen. This indicator is similar to risk aversion. This indicator was applied in CASES project, PSI and NEEDS projects [32–38].

Table 4 summarizes electricity and heat generation technologies which will be assessed in terms of the previously described sustainability assessment indicators framework (Table 1).

The initial decision matrix is given in Table A.1. The first three rows describe criteria: *MIN* denotes cost criteria, whereas *MAX* – benefit criteria. There are 13 the long-term sustainability indicators consisting of 5 economic indicators (private costs, grid costs, availability factor, peak load response and security of supply), 4 environmental (environmental external costs, radionuclides external costs, human health related external costs, GHG emissions), and 4 social indicators (technology-specific job opportunities, food safety risks, fatal accidents from the past and severe accidents perceived in the future). Respective rows describe each of 33 electricity production technologies under consideration.

4. Results of the multi-criteria assessment

In order to compare the 33 electricity production technologies listed in Table 4 against sustainability criteria (cf. Table 1) the data were aggregated into decision matrix (cf. Table A.1). In order to test the sensitivity of the results, the four different scenarios were defined (Table 5).

As one can note the first scenario is a holistic one, where every of the sustainability dimensions is treated as equally important. The following three scenarios put the most of significance on economic, environmental, or social factors, respectively. More specifically, weights for certain criteria were obtained by dividing indicator group's weight by the number of indicators in that group (i.e. cardinality). For instance, the five economic indicators were attributed with uniform weights equal to $0.5/5 = 0.1$ according to the economic approach. Subsequently the two MCDM methods, namely MULTIMOORA and TOPSIS, were applied.

Firstly, the decision matrix (Table A.1) was normalized by employing Eq. (1). Thereafter Eq. (2) was applied for the Ratio System, which enabled to rank the alternatives. Electricity production technologies were also ranked according to the Reference Point by employing Eq. (3). In order to successfully apply the Full Multiplicative Form, the observed zero values in decision matrix were replaced with penalty values of 0.001. Then Eq. (4) was employed for ranking of the alternatives.

As for TOPSIS, Eqs. (5) and (6) were applied in order to define positive- and negative-ideal solutions. It was followed by computation of distances from the latter two solutions for each of alternatives under consideration (Eqs. (7) and (8)). Finally, these distances were aggregated into closeness coefficient for each alternative (Eq. (9)). The alternatives were thus ranked in descending order of the closeness coefficient.

Indeed, the procedure was repeated for each of scenario defined in Table 5. Thus, Table 6 presents the results. As one can note, renewable energy sources-based technologies were the most preferable ones according to every approach.

Ranking with equal significance of every sustainability dimension (i.e. holistic approach) suggests hydro power (HYD M, HYD L, HYD S) and solar thermal (SOL TH) technologies being the most sustainable. However, TOPSIS method placed wood chips CHP (CHP WOOD) at the very top.

Table 5
Criteria weights under different scenarios.

Criteria	Holistic approach	Economic approach	Environmental approach	Social approach
Economic indicators	0.33	0.5	0.25	0.25
Environmental indicators	0.33	0.25	0.5	0.25
Social indicators	0.33	0.25	0.25	0.5

Table 6
The ranks provided for different electricity production technologies in terms of different methods and scenarios.

Rank	Holistic approach		Economic approach		Environmental approach		Social approach	
	MULTIMOORA	TOPSIS	MULTIMOORA	TOPSIS	MULTIMOORA	TOPSIS	MULTIMOORA	TOPSIS
1	HYD M	CHP WOOD	HYD M	CHP WOOD	SOL TH	CHP WOOD	HYD M	HYD L
2	HYD L	SOL TH	HYD L	HYD L	HYD M	SOL TH	SOL TH	HYD M
3	SOL TH	HYD L	HYD S	HYD M	HYD L	HYD L	HYD DAM	SOL TH
4	HYD S	HYD M	HYD DAM	HYD S	HYD S	HYD M	WIND ON	HYD S
5	HYD DAM	HYD S	CHP WOOD	CHP COAL CCS	HYD DAM	HYD S	PV ROOF	HYD DAM
6	HYD PMP	HYD DAM	HYD PMP	SOL TH	HYD PMP	HYD DAM	PV OPEN	HYD PMP
7	WIND ON	HYD PMP	CHP COAL CCS	HYD DAM	WIND ON	HYD PMP	HYD L	CHP WOOD
8	CHP WOOD	CHP GAS CCS	SOL TH	HYD PMP	WIND OFF	PV ROOF	HYD S	PV OPEN
9	CHP COAL CCS	SOFC	CHP STRAW	CHP STRAW	CHP COAL CCS	CHP GAS CCS	HYD PMP	PV ROOF
10	WIND OFF	CHP COAL CCS	CHP COAL BP	CHP GAS CCS	CHP WOOD	WIND OFF	CHP WOOD	CHP GAS CCS
11	SOFC	CHP STRAW	COA IGCC CCS	SOFC	PV OPEN	WIND ON	WIND OFF	WIND OFF
12	CHP GAS CCS	WIND ON	SOFC	GAS STAG	SOFC	PV OPEN	CHP GAS CCS	WIND ON
13	COA IGCC CCS	WIND OFF	WIND ON	COA IGCC CCS	PV ROOF	SOFC	SOFC	SOFC
14	PV ROOF	CHP GAS	WIND OFF	CHP GAS	GAS STAG	CHP COAL CCS	CHP COAL CCS	CHP GAS STAG
15	CHP STRAW	GAS STAG	COA CL	CHP GAS STAG	COA IGCC CCS	CHP GAS	CHP STRAW	CHP GAS
16	PV OPEN	CHP GAS STAG	LIG IGCC	WIND ON	CHP GAS CCS	GAS STAG	GAS STAG	GAS STAG
17	LIG IGCC	PV OPEN	CHP GAS CCS	WIND OFF	CHP STRAW	CHP GAS STAG	MCFC	CHP STRAW
18	CHP COAL BP	COA IGCC CCS	GAS STAG	CHP COAL	CHP GAS	COA IGCC CCS	COA IGCC CCS	MCFC
19	GAS STAG	PV ROOF	PV ROOF	COA IGCC	LIG IGCC	LIG IGCC CCS	CHP COAL BP	GAS GT
20	MCFC	MCFC	GAS GT	MCFC	CHP COAL BP	GAS GT	COA CL	CHP COAL CCS
21	CHP COAL	GAS GT	MCFC	GAS GT	GAS GT	MCFC	GAS GT	MCFC
22	COA CL	CHP COAL	CHP COAL	CHP COAL BP	MCFC	CHP STRAW	MCFC	COA IGCC CCS
23	GAS GT	COA IGCC	OIL CL	LIG IGCC CCS	CHP GAS STAG	COA IGCC	CHP COAL	CHP COAL
24	OIL CL	LIG IGCC CCS	CHP GAS	COA CL	CHP COAL	CHP COAL	CHP GAS	COA IGCC
25	CHP GAS	OIL GT	CHP GAS STAG	LIG IGCC	GAS STAG CCS	OIL GT	CHP GAS STAG	OIL GT
26	CHP GAS STAG	CHP COAL BP	PV OPEN	LIG CL	LIG IGCC CCS	LIG IGCC	GAS STAG CCS	LIG IGCC CCS
27	COA IGCC	LIG IGCC	COA IGCC	OIL GT	COA IGCC	OIL CL	COA IGCC	OIL CL
28	OIL GT	COA CL	LIG CL	OIL CL	COA CL	LIG CL	OIL GT	GAS STAG CCS
29	MCFC	OIL CL	OIL GT	PV OPEN	OIL CL	CHP COAL BP	NUC	CHP COAL BP
30	GAS STAG CCS	LIG CL	MCFC	MCFC	LIG CL	COA CL	LIG IGCC	LIG IGCC
31	LIG IGCC CCS	MCFC	GAS STAG CCS	PV ROOF	OIL GT	MCFC	OIL CL	COA CL
32	LIG CL	GAS STAG CCS	LIG IGCC CCS	GAS STAG CCS	MCFC	GAS STAG CCS	LIG IGCC CCS	LIG CL
33	NUC	NUC	NUC	NUC	NUC	NUC	LIG CL	NUC

Meanwhile, the economic approach is also related with similar technologies with exception of solar thermal energy (SOL TH) which is no longer among the most sustainable technologies. At the other end of spectrum, wood and coal CHP (CHP WOOD, CHP COAL) graduated in the technology list.

The environmental approach supports solar energy, hydro energy and wood CHP. Finally, the social approach suggests hydro (HYD L, HYD M, HYD DAM), solar thermal (SOL TH), and on-shore wind (WIND ON) electricity production.

Noteworthy, the multi-criteria assessment rated the conventional energy technologies (oil, gas, coal, nuclear) as the most unsustainable.

5. Conclusions

The selected energy technologies were assessed on a basis of information gathered during the projects dedicated to the long-term assessment of these technologies. The two MCDM methods—MULTIMOORA and TOPSIS—were employed in order to obtain more robust results. These methods are based on different utility functions and thus enable to assess alternatives against multiple criteria in an integrated manner.

The multi-criteria analysis showed that renewable energy sources-based electricity production technologies are to be preferred. To be specific, hydro and solar power systems were identified as the most sustainable, whereas wood CHP and wind power remained some positions behind. At the other end of spectrum, conventional energy technologies, namely oil, gas, coal, and nuclear power, were the most unsustainable. The future energy policy, therefore, should be oriented towards the sustainable energy technologies ensuring economical, societal, and environmental growth. Thus it should involve MCDM into strategic management processes. Moreover, the financial incentives should be directed in accordance with integrated assessment of energy technologies.

Given the different level of energetic and economic development across different states, the regional sub-optimization should also take place. It would enable to identify the most suitable energy technologies for particular region specific with certain features.

Further studies should be focused on multi-criteria analysis of sustainable energy production technologies by employing fuzzy logics and thus tackle the uncertainty associated with suchlike assessments.

Appendix A. Appendix A

Initial data on electricity production technologies.

Table A.1
The decision matrix for long-term sustainability assessment of EU electricity technologies in 2030.

Technology	HEALTH EURcnt/kWh MIN	CO_2eq. kg/kWh MIN	PR COST EURcnt/kWh MIN	ENV EURcnt/kWh MIN	RADIO EURcnt/kWh MIN	ACC PAST Fatal./kWh MIN	ACC FUT Point MIN	FOOD Point MIN	GRID COST Point MIN	AVAILAB Per cent MAX	SECURE Point MAX	PEAKLOAD Point MAX	EMPL Person-year/kWh MAX
NUC	0.19	0.013	2.653	0.015	0.1452	0.001	4	1	3	0.9	4	0.5	0.16
OIL CL	2.39	0.208	7.194	0.213	0.0017	0.132	4	1	3	0.85	1	5	0.47
OIL GT	1.853	0.435	9.681	0.174	0.0019	0.132	4	1	3	0.85	3	5	0.47
COA CL	1.548	0.751	3.203	0.186	0.0012	0.157	4	1	3	0.85	3	2.5	0.86
COA IGCC	0.93	0.694	3.495	0.105	0.0013	0.157	4	1	3	0.85	3	2.5	0.86
COA IGCC CCS	1.042	0.154	4.15	0.118	0.0005	0.157	4	1	3	0.85	3	2.5	0.86
LIG CL	1.134	0.817	2.135	0.13	0.0005	0.157	4	1	3	0.85	3	1	0.21
LIG IGCC	0.934	0.786	2.778	0.094	0.0005	0.157	4	1	3	0.85	3	1	0.21
LIG IGCC CCS	1.051	0.106	3.351	0.106	0.0002	0.157	4	1	3	0.85	0	1	0.21
GAS STAG	0.563	0.395	4.519	0.077	0.0002	0.085	2	1	3	0.85	0	5	0.65
GAS STAG CCS	0.62	0.11	5.875	0.86	0.0002	0.085	2	1	3	0.85	0	5	1.8
GAS GT	0.864	0.62	6.563	0.124	0.0002	0.085	2	1	3	0.85	0	5	0.65
HYD S	0.198	0.013	7.229	0.016	0.0001	0.001	1	1	3	0.8	5	1.5	1.2
HYD M	0.142	0.009	4.519	0.011	0.0001	0.001	1	1	3	0.8	5	1.5	1.2
HYD L	0.127	0.008	4.519	0.01	0.0002	0.001	1	1	3	0.8	5	1.5	1.2
HYD DAM	0.245	0.015	7.35	0.02	0.0002	0.001	2	1	3	0.91	5	1.5	1.2
HYD PMP	0.251	0.014	7.35	0.02	0.0005	0.001	2	1	3	0.91	5	1.5	1.2
WIND ON	0.142	0.01	6.019	0.007	0.0004	0.001	1	1	4	0.29	5	0	0.36
WIND OFF	0.173	0.007	6.143	0.006	0.0022	0.001	1	1	5	0.5	5	0	0.36
PV ROOF	0.479	0.056	25.14	0.032	0.0028	0.001	1	1	3	0.15	5	0	6.6
PV OPEN	1.082	0.108	20.829	0.064	0.0002	0.001	1	1	3	0.15	5	0	6.6
SOL TH	0.105	0.008	11.969	0.007	0.0002	0.001	1	1	3	0.15	5	0	6.6
CHP GAS	0.527	0.366	4.225	0.072	0.0002	0.085	2	1	4	0.85	0	5	0.65
CHP GAS CCS	0.574	0.101	5.45	0.079	0.0011	0.085	2	1	4	0.85	0	5	1.8
CHP COAL	1.406	0.674	0.945	0.167	0.001	0.157	4	1	4	0.85	3	2.5	2.01
CHP COAL CCS	0.805	0.119	1.468	0.092	0.0002	0.157	4	1	4	0.85	3	2.5	2.01
CHP GAS STAG	0.612	0.424	4.134	0.083	0.0012	0.085	2	1	4	0.85	0	5	0.86
CHP COAL BP	1.555	0.741	0.503	0.183	0.0004	0.157	4	1	4	0.85	3	2.5	0.86
CHP STRAW	1.691	0.069	4.751	0.36	0.0029	0.085	2	2	4	0.95	5	5	4.4
CHP WOOD	0.639	0.057	3.791	0.078	0.0028	0.085	2	2	4	0.95	5	5	4.4
MCFC	1.958	0.184	7.3	0.167	0.0018	0.085	2	1	3	0.95	3	0.5	1.8
SOFC	0.664	0.127	7.08	0.069	0.0005	0.085	2	1	3	0.95	3	0.5	1.8
MCFC BG	3.196	0.326	7.824	0.241	0.0027	0.085	2	1	3	0.95	3	0.5	1.8

See Tables 1 and 4 for acronyms of criteria and energy production technologies, respectively.

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